



University of Wales Trinity Saint David

CYLINDER HEAD ANALYSIS

Data Collection

Eduardo Aguilar

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1. Introduction

There are different forms in the automotive and motorsport world to increase the power of a CI. However all of them have the same common factors: getting more air and fuel into the combustion chamber, making the engine more efficient and the exhaust quicker and smoothly as possible increasing in the same time the intake airflow. Cylinder head porting could bring more output power due to the direct relationship between the mass flow rate of air into an engine and the power capable of being developed, it's vital to get as much air as possible (with the correct amount of fuel)(Peter Burgess & David Gollan).

The following assignment will explain how could compare two different cylinder heads through a flow bench test, measuring the air flow from the intake and the exhaust port of each cylinder head to improve the volumetric efficiency of the system. There are several factors that could improve movement and the quantity of the air intake and different ways to analyse the engine external and internal processes. The following sections will describe what is a flow bench, how the measurements were taken, the data collected through the flow bench and the analysis. Finally, how could improve the cylinder heads based on the data collected.

2. Research

2.1 Cylinder Heads

Cylinder head can be made of cast iron or aluminium alloy. Head must be rigid enough to keep the gases inside the combustion chamber during the 4 strokes cycle. During casting process cast flash can occur, caused by the metal leaking from joints in the cast. Once the base of the material of the head is manufactured, a CNC machine is used to mill out the valve seats and other small chamfers to complete the head design. Cylinder head is designed to contain passages for coolant, spark plugs, valves..etc.

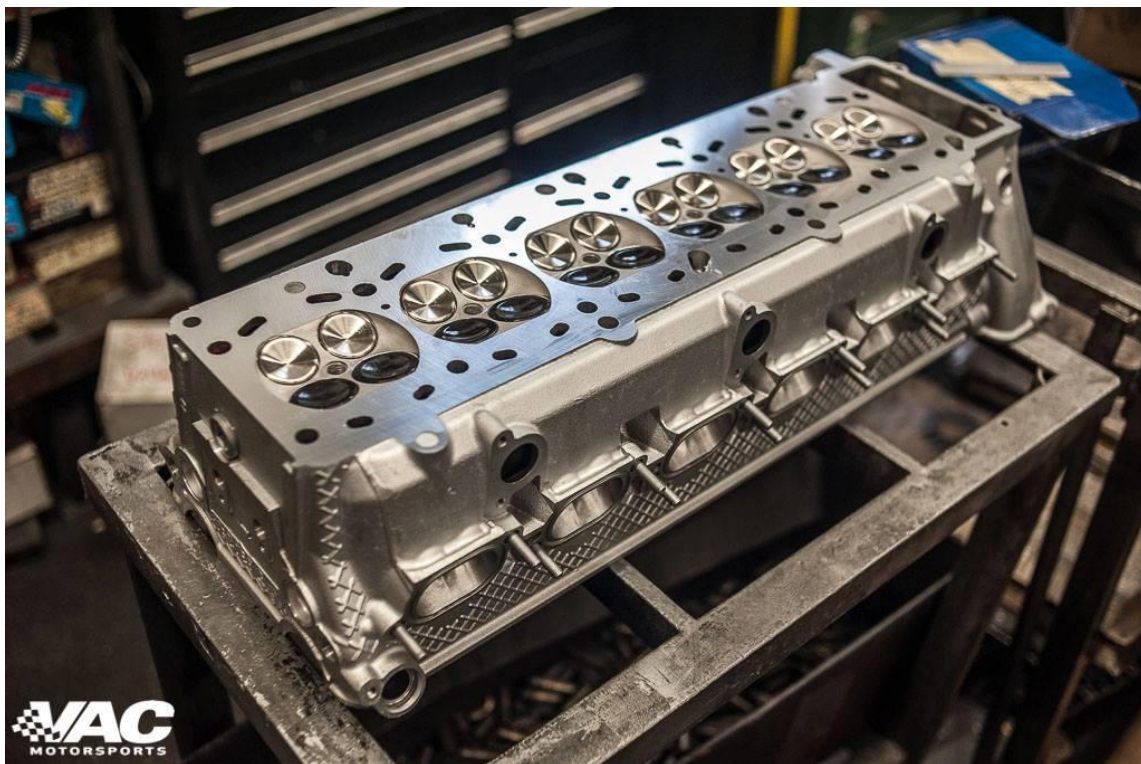


Figure 1; BMW s54 cylinder head top view (valves, coolant passages and exhaust ports)

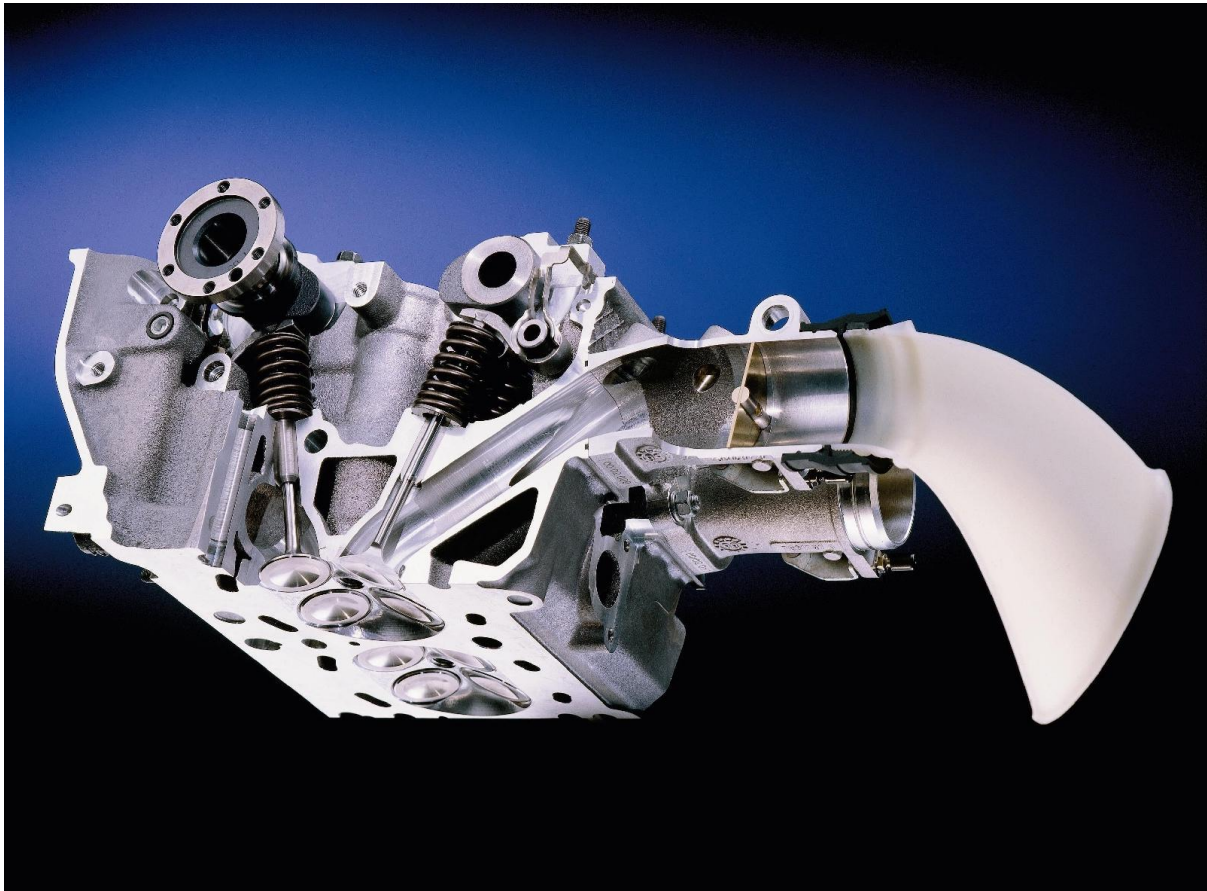


Figure 2: s54 Cylinder head, inlet ports at the right and interior valves.

The majority of modern engines are of **overhead** valve design (OHV), which allows compact efficient combustion due to the shape in the inside chamber. The overhead chamber is been designed with the valves placed in the cylinder head, it was an improvement in comparison with the flathead engine (OHC), where the valve were situated in the block next to the piston. The principal advantage of the overhead engines is the block volume; due to the camshaft location provide less space to assembly the components of the engine, the complicity of the engine is less due to the camshaft location is closer to the crankshaft and that allows shorter timing belt and chains. The last advantage to use this type of cylinder head is the use of hydraulic lifters, providing an increase of the RPM and the life of the engine by reducing the maintenance of it.

Overheads engine can be single (SOHC) or double (DOHC) camshaft, and these cams may operate the valves either directly, trough action on bucket followers, or indirectly via finger followers or rockers.

2.1.1 Type of Cylinder Heads

- **Inline OHV:** Valves are generally arranged vertically, with bathtub, and shaped combustion chambers.
- **Heron Head:** OHV engine with inline valves and the combustion chamber in the piston
- **Wedge Head:** Valves are inline but with an angle from the vertical, creating a wedge-shaped combustion chamber
- **Pent-Roof:** Valve heads are opposed in a sloping sided combustion chamber. Are very common in the actual 4 valve per cylinder layouts.
- **Hemi Head:** The valve heads are opposed, the chamber is hemispherical.

- **Flathead Chamber:** Older design for valves contained in the cylinder.

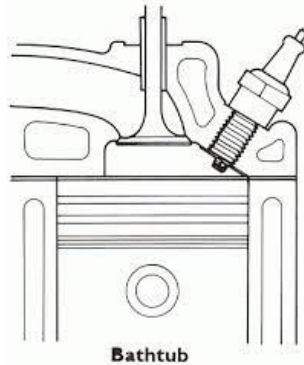


Figure 3: Wedge Cylinder Head

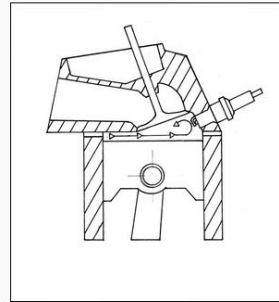


Figure 4: Inline Cylinder head

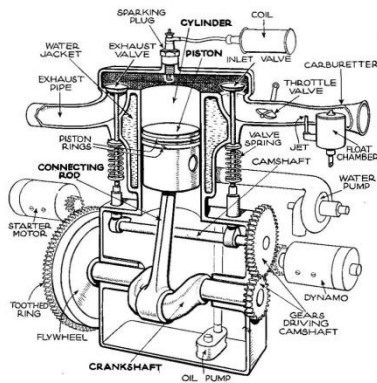


Figure 6: Sidevalve

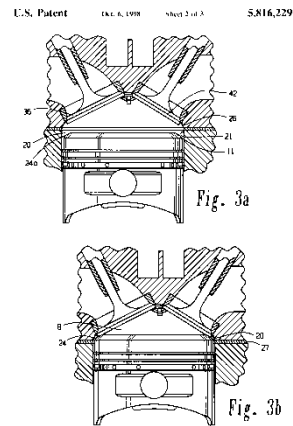


Figure 5: Hemi Head

1.1 Fundamentals of Airflow

Squish

Is the descriptive name given to the random movement of the yet unburned air and fuel mixture in the cylinder, caused by the piston nearing the cylinder towards the end of the compression stroke. In most cases, the part of the piston crown and the cylinder head are pretty close at TDC generating a fairly high speed. Mixture caught between these surface is squirted out of the way, the easiest way for the air to escape is into the main body of the mixture already in the combustion chamber. The principal mixture is now ready to the combustion chamber waiting for the spark ignition. The turbulent movement helps the air to mix together, resulting a better combustion.

Swirl and Tumble

Swirl is the name of rotational fluid mass generated within the cylinder, is very usual in modern engine cylinder heads due to can improve the power of the engine and also reduce the emissions and fuel consumption of the engine. Can be created by using port design to direct the incoming mixture.

The port can be either curved to direct the flow past valve or have a deflector in it to force the flow out. The principal intention is to come into the cylinder as a tangent and organise the mixture through all the cylinder travel.

Tumble is another form of Swirl, generated by the influence of the shape of the ports. The difference between the swirl and the tumble is that in the last one, the rotational motion is parallel to the top of the piston, it occurs in a different axis.

Another and more complex way to create movement within himself is called helical ports, and creates a swirl. Helical ports have a greater volumetric efficiency than the other types, but there are very uncommon to modify.

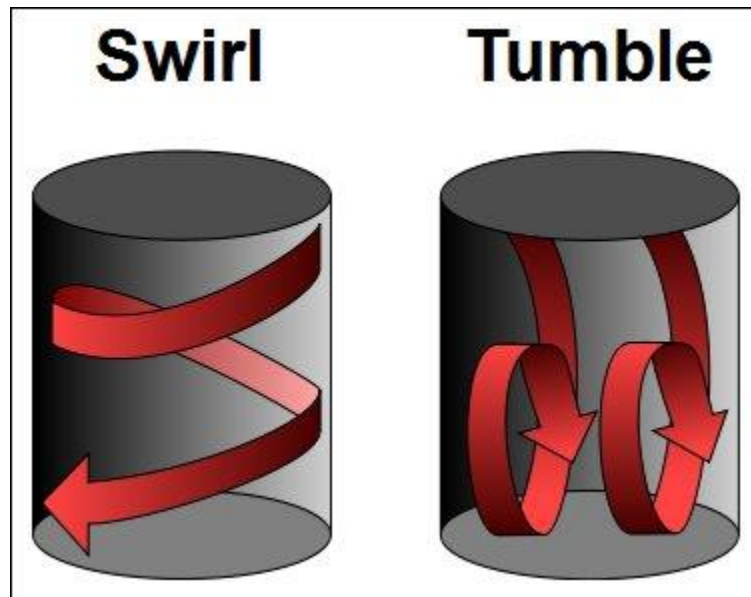


Figure 7: Swirl and Tumble Directions inside the piston

Airflow is more sensitive to shape than size, so big ports are not necessarily better than small ports at flowing air. Airflow also is not very good in changes of directions, volume and/or shape. As this assignment said in the beginning, improving the volumetric efficiency is the key to good usable power gains.

'Volumetric efficiency is defined by as the ratio of the volume of the air drawn into the engine to the engine's swept volume'. The speed of the air travel through the port depends upon the volume of the cylinder, the speed of the engine and the size of the port.

A small port and a large cylinder will have a high air mass speed at low RPM, and it will be unable to support speed at high RPM. In the other hand, a large port and same cylinder will only achieve high gas speed at high RPM, and low gas speed at low RPM.

2.2 Air Flowbench

Definition

A flowbench is designed to measure the air-flow resistance of the engine cylinder heads, intake manifolds and other items reading the drop in the air pressure along the circuit measured by a manometer.

What is a Flow Test?

Is a test consisting of sucking or blowing air through the cylinder head at constant pressure. The flow rate is measured at various valve lifts (measured by DTI in each valve). If any improvement is made

in the cylinder head to improve the swirl, or any air movement, the flow bench air flow will indicate a greater air flow of the system.

How it works?

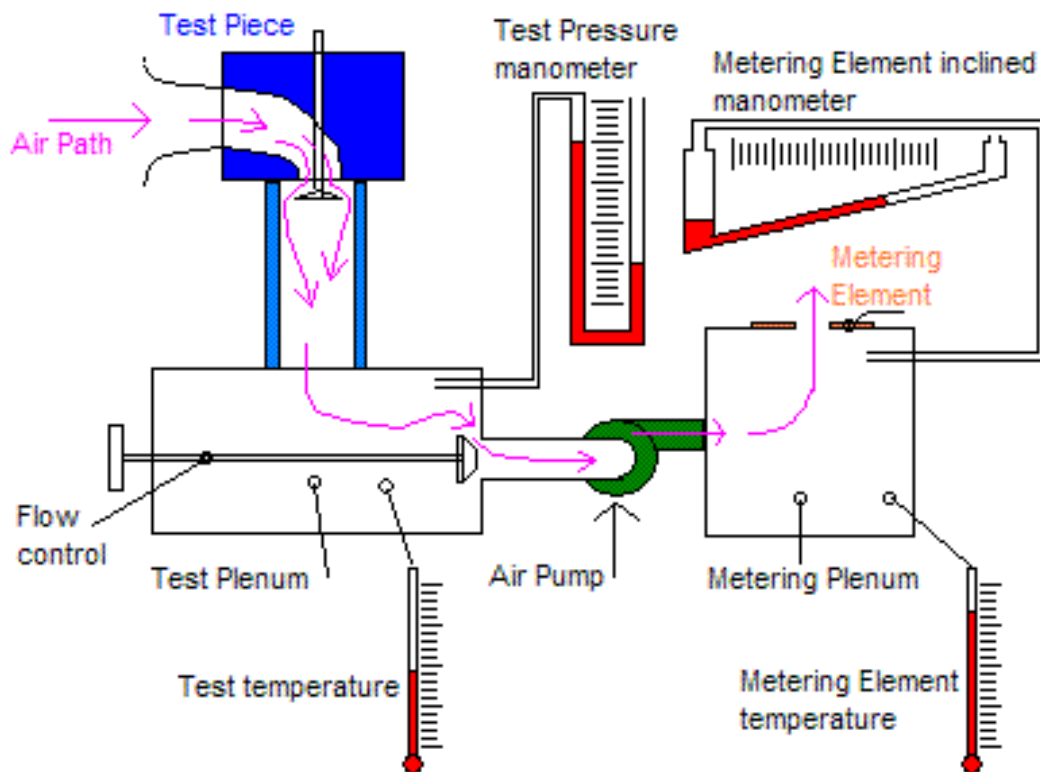


Figure 8: Flow bench example

For intake testing, air is sucked from the environment to the cylinder head through the air pump, from the cylinder head the air comes to the test plenum (at same pressure for every calculation, and measured by the test pressure manometer), then come into the orifice plate (metering plenum) regulated by the flow control knob and measured by the inclined flow meter reading percent flow for the different orifices of the flowbench. For exhaust testing, the path of the airflow is reversed.

3. Methodology

A test for two different head cylinder was carried out to measure the inlet and exhaust port of each head cylinder. The entire test was measured by the Super Flow SF-300/600 Flow bench.

The First head cylinder was a Rover K series 1.8L and the port measured was the number 1. Cylinder heads are mounted into the flow bench by a cylinder adapter. The adapter is a tube of four inches long with the same bore as the engine and a flange on the end. The lower flange is bolted to the flow tester and the upper flange is bolted to the cylinder head. Both flanges were being flat with the surface to be seal. Before installing the test adapter, a test orifice plate was installed onto the bench. Once installed the test adapter, the flow bench was turned on, the flow range selector was in the position 1, and the direction and of the flow in intake below 150 cfm.

The test pressure meter and the inclined flow meter were levelled to zero. With a small quantity of the test orifice open, the motor was turned ON and slowly the intake flow control was opened until the test pressure reaches 25 inches of water (is a non-SI unit pressure to measure the difference of pressure between 2 orifices, is used in USA).

1 inches of water = 248.84 Pa at 4 Celsius Degrees

The leakage from the system was zero, measured by the flow meter. The leakage will not affect the test instead would be different zero due to the posterior correction on the data sheets.

The intake valve was opened to the first lift point, the ratio on every test were the same; the valve diameter of each valve was multiplied by the L/D ratios (0.05 increments) to finally obtain the valve lift points. The first amount of the first valve lift was recorded in the data sheet and the first flow percentage in the inclined flow meter was recorded.

If the flow meter reading exceeded 100% before reach the constant 25 inches of water of pressure, the next flow range was selected. This flow range also is critical to make the good conversion of air-flow in the posterior data sheets. The values of calibration from the flow ranges were printed in the Calibration Data Card at 25 inches of water.

Finally 8 different test were recorded applying different flow range at different valve lifts at 25 inches of water. To measure the exhaust the path of the air flow was reversed and is was switched in the front control panel. Another 8 different valve lifts were recorder for the exhaust ports.

The same patter applied for the Rover K series was applied for the Ford 1.6 engine. 8 valve lifts and airflows were recorded for the inlet and another 8 valve lifts and airflow for the exhaust.

The accuracy in the reading was very important due to the final result was the product of multiplications in different flow-scales.

The following data was recorded during the test and every row and column will be explained to understand and explain the veracity of each result.

2. Results

a. Rover K Series 1.8L

Test Setup Data		ROVER K SERIES 1.8L			
	Valve Head Diameter (mm)	Valve Steam Diameter (mm)	Valve Head Diameter (in)	Valve Steam Diameter (in)	Effective Valve Area
Intake	27.700	6.450	1.091	0.254	0.883
Exhaust	24.000	5.970	0.945	0.235	0.657

Valve lift/Diameter (L/D)	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40
Intake Valve Lift (mm)	1.39	2.23	4.16	5.55	6.93	8.31	9.69	11.08
Exhaust Valve lift (mm)	1.20	2.40	3.60	4.80	6.00	7.20	8.40	9.60

Range	1	2	3	4	5	6
Intake	34.98	70.98	147.76	292.98	440.53	595.54
Exhaust	41.43	78.652	159	314.82	465.55	603.35

Test number	1	2	3	4	5	6	7	8
Test Pressure	25	25	25	25	25	25	25	25
Valve Lift	1.39	2.23	4.16	5.554	6.93	8.31	9.69	11.08
Flow Range	1	2	3	3	3	3	4	4
Flowscale %	93.5	89	61	74.8	84.1	90	45.5	47
Flowscale (1/1)	0.935	0.89	0.61	0.748	0.841	0.9	0.455	0.47
Raw Test Flow CFM	32.7063	63.1722	90.1336	110.5245	124.2662	132.984	133.3059	137.7006
Leakage (Flowscale % when valves are shut)	0	0	0	0	0	0	0	0
Test CFM	32.7063	63.1722	90.1336	110.5245	124.2662	132.984	133.3059	137.7006
Test CFM/(sq/in)	37.03998	71.5427	102.0766	125.1693	140.7318	150.6048	150.9693	155.9463
Potential Flow	25.3	47.3	65.7	74.2	79.5	82.6	82.6	82.6
%Potential Flow	1.464031	1.512531	1.553677	1.686918	1.770211	1.823302	1.827716	1.88797

Test number	1	2	3	4	5	6	7	8
Test Pressure	25	25	25	25	25	25	25	25
Valve Lift	1.2	2.4	3.6	4.8	6	7.2	8.4	9.6
Flow Range	1	1	2	2	2	3	3	3
Flowscale %	50	96.5	74	88	96	57	61.5	65
Flowscale (1/1)	0.5	0.965	0.74	0.88	0.96	0.57	0.615	0.65
Raw Test Flow CFM	20.715	39.97995	58.20248	69.21376	75.50592	90.63	97.785	103.35
Leakage (Flowscale % when valves are shut)	0	0	0	0	0	0	0	0
Test CFM	20.715	39.97995	58.20248	69.21376	75.50592	90.63	97.785	103.35
Test CFM/(sq/in)	31.52968	60.85228	88.58825	105.3482	114.9253	137.9452	148.8356	157.3059
Potential Flow	25.3	47.3	65.7	74.2	79.5	82.6	82.6	82.6
%Potential Flow	1.246232	1.286518	1.348375	1.419787	1.445601	1.670039	1.801884	1.90443

4.2 Ford 1.6

Test Setup Data			Ford 1.6		
	Valve Head Diameter (mm)	Valve Steam Diameter (mm)	Valve Head Diameter (in)	Valve Steam Diameter (in)	Effective Valve Area
Intake	30.04	5.94	1.185	0.256	1.05
Exhaust	24.13	5.97	0.95	0.243	0.66

Valve lift/Diameter (L/D)	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4
Intake Valve Lift (mm)	1.5	3	4.5	6	7.51	9.01	10.51	12.01
Exhaust Valve lift (mm)	1.2	2.41	3.61	4.82	6.03	7.23	8.44	9.65

	Range	1	2	3	4	5	6
	Intake	34.98	70.98	147.76	292.98	440.53	595.54
	Exhaust	41.43	78.652	159	314.82	465.55	603.35

Test number	1	2	3	4	5	6	7	8
Test Pressure	25	25	25	25	25	25	25	25
Valve Lift	1.502	3	4.5	6	7.51	9.01	10.51	12.01
Flow Range	2	3	3	3	4	4	4	4
Flowscale %	56.5	56.7	81	95	48	48.5	49	49.5
Flowscale (1/1)	0.565	0.567	0.81	0.95	0.48	0.485	0.49	0.495
Raw Test Flow CFM	40.1037	83.77992	119.6856	140.372	140.6304	142.0953	143.5602	145.0251
Leakage (Flowscale% when valves are shut)	0	0	0	0	0	0	0	0
Test CFM	40.1037	83.77992	119.6856	140.372	140.6304	142.0953	143.5602	145.0251
Test CFM/(sq/in)	38.194	79.7904	113.9862857	133.687619	133.9337	135.3289	136.724	138.1191
Potential Flow	25.3	47.3	65.7	74.2	79.5	82.6	82.6	82.6
%Potential Flow	1.50964427	1.68690063	1.734951076	1.801719933	1.684701	1.638364	1.655254	1.672145

Test number	1	2	3	4	5	6	7	8
Test Pressure	25	25	25	25	25	25	25	25
Valve Lift	1.2	2.41	3.61	4.82	6.03	7.23	8.44	9.65
Flow Range	1	2	2	3	3	3	3	3
Flowscale %	66	60.5	84.5	53	57	60.5	62.5	64.5
Flowscale (1/1)	0.66	0.605	0.845	0.53	0.57	0.605	0.625	0.645
Raw Test Flow CFM	27.3438	47.58446	66.46094	84.27	90.63	96.195	99.375	102.555
Leakage (Flowscale% when valves are shut)	0	0	0	0	0	0	0	0
Test CFM	27.3438	47.58446	66.46094	84.27	90.63	96.195	99.375	102.555
Test CFM/(sq/in)	41.43	72.09767	100.6984	127.6818	137.3182	145.75	150.5682	155.3864
Potential Flow	25.3	47.3	65.7	74.2	79.5	82.6	82.6	82.6
%Potential Flow	1.637549	1.524264	1.5327	1.720779	1.727273	1.764528	1.822859	1.881191

With these tables a graph will be plot to see the airflow against the valve lift in different units and to compare the differences between the 2 cylinder head.

First table correspond to the calculations of the effective valve area, also called net valve area, is the difference in inches between the valve diameter and the valve steam and is the area were the air pass into the head.

$$\text{Effective valve area} = 0.785 (\text{Valve Head Diameter in inches})^2 - (\text{Valve Steam diameter in inches})^2$$

The second table shows the relation between the valve lift and the diameters. To calculate the intake and the exhaust valve lift so show the flow efficiency to be compare regardless of the size, the valve diameter was multiplied by the 8 L/D ratios (from 0.05 to 0.40).

$$\text{Valve lift} = L/D \text{ ratios} \times \text{Exhaust/Inlet Diameter in mm}$$

Range table is scale of the airflow between the different orifices of the flow bench, permit change the orifices or the flow bench of the pressure increases 100% of the 25 inches of water manometer. This relation is crucial to calculate the air flow and is shows in pink colour at the front part of the flow bench.

The bigger table show the calculations to plat the graphs and finally make conclusions for the final part of the assignment; the different columns will be explained in the following lines:

Test pressure: Shows the test pressure along the test, was constant and the value was 25 inches of water.

Valve lift: Explained before. Measured previous the multiplication by the DTI.

Flow range: Explained before, is the range table and the values are from 1 to 4.

Flows cale: Percentage of flow measured in the incline manometer.

Flow scale 1/1: Value of the flow scale in decimal number.

Raw Test Flow: One of the most important calculations. The result shows the airflow measured by the inclined manometer in percentage multiplied by the corresponding air flow data from the Calibration Card in function of the flow range.

$$\text{Raw Test Flow: Flow Scale} \times \text{Range of the calibration data in function of the flow range}$$

Leakage: Zero for the system used in the workshop along the test.

Test CFM: Is the corrected Raw Test flow in function of the leakage, as the leakage is zero, the corrected data is the same as the Raw Test flow.

Test CFM/sq inches: Is the airflow divided by inches square, it means the airflow come through the effective valve area.

$$\text{Test CFM/inches}^2 = \text{Test CFM} / \text{Effective Valve area in inches}^2$$

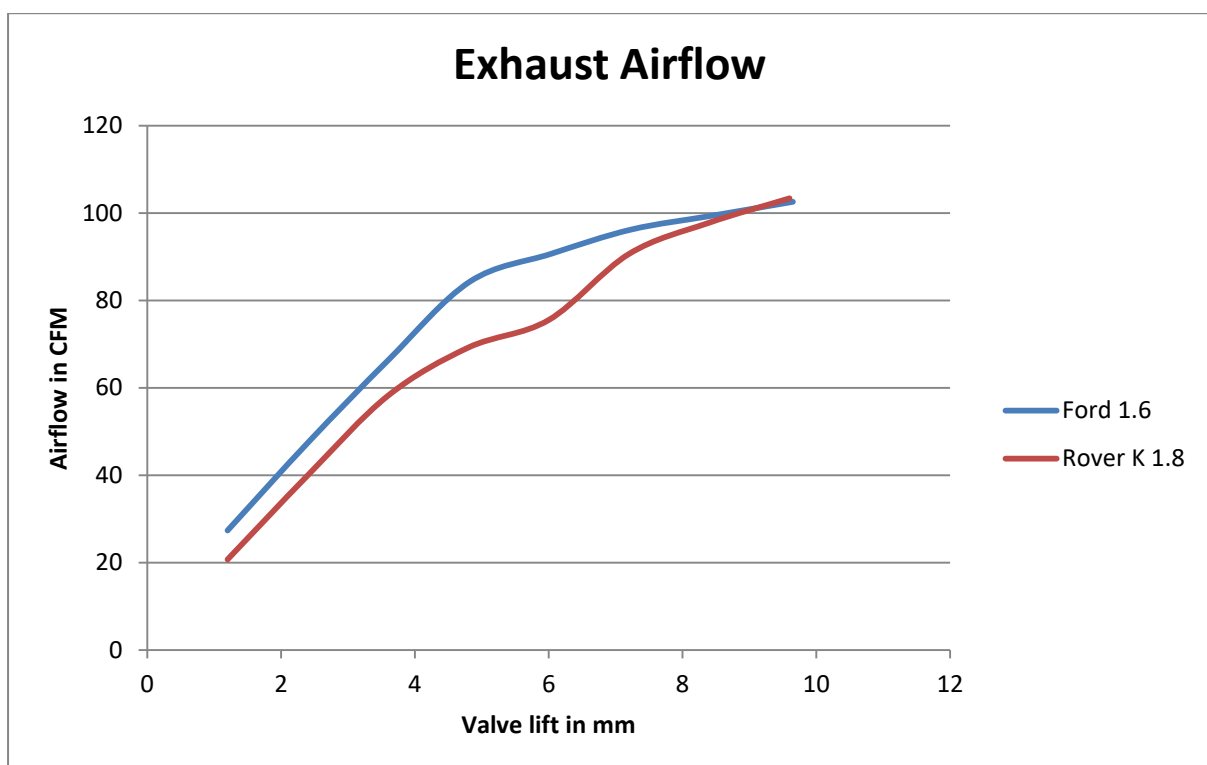
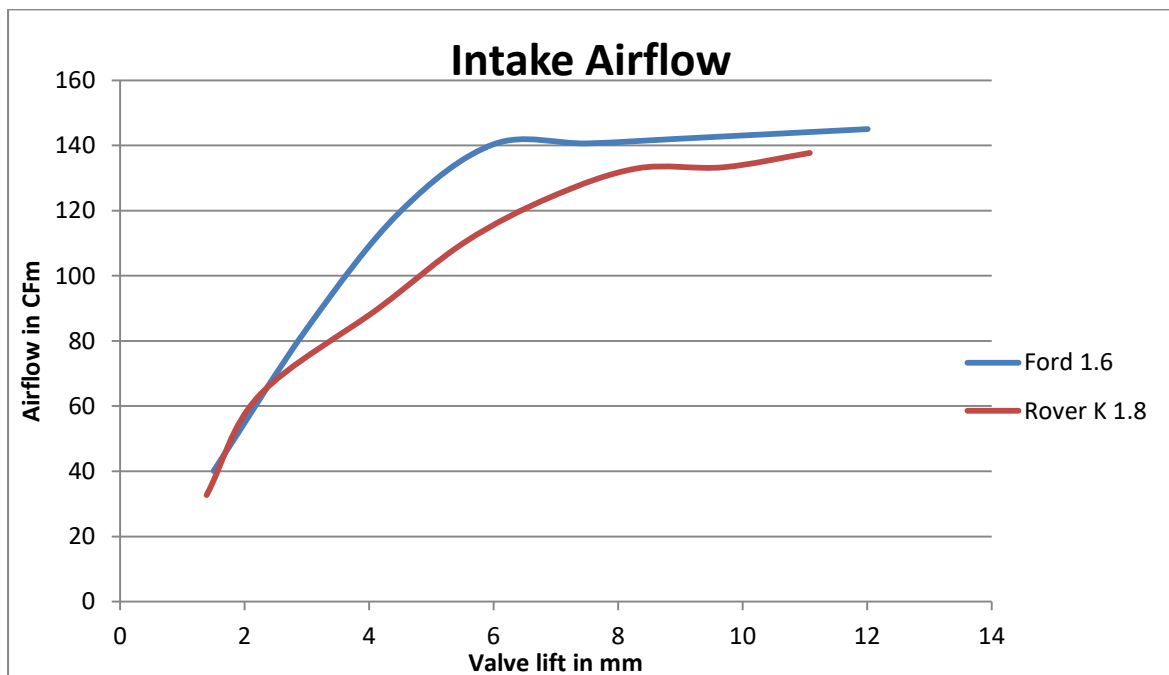
Potential flow: Obtained from the table of the SF-300/600 operators manual for Hemi-Intake and all exhaust valves in UK units. At 25 inches of pressure.

% Potential Flow: It shows the how much can improve the airflow of the test. It was calculated by the following formula and is basically a comparison of the airflow measured in other system.

$$\% \text{ Potential flow} = \text{Test CFM/Inches square} / \text{Potential flow}$$

3. Analysis and graphs

5.1 CFM vs Valve lift



Analysis of Intake Graph

The Ford 1.6 intake graph shows an exponential pattern of the airflow through the intake port. From **1.5 mm** of valve lift to **6 mm** the slope of the function is very high, it means the airflow is increasing highly into the inlet port allowing the airflow good speed at slow-mid valve lifts. What is happening just after, at **7.51mm valve lift and 0.25 L/D** is a drop in the air flow through the intake-port. As the assignment explains in the research section, there are several factors involving the air flow of the port and different direction of the flow inside the chamber. At low RPM, it means at low air flow, the swirl, tumble and turbulences are very smooth, but when the flow is increasing, also the forces applied in these movements increase as well. So the movement inside the chamber is mixing in all directions and then causes a non-controlled flow direction inside the chamber which decreases the power, efficiency and fuel of the system. From the big drop, the graph shows a nearly linear pattern flow inside the chamber, this factor is due the intake port cannot conduct in a proper direction the air and the quantity vacuum inside the port per inch is will be more or less the same due the characteristic of the port.

In the **Rover K series** cylinder head the first exponential pattern **from 1.39mm** has minor slope and is higher, up to almost **8.31 mm valve lift. (drop is at 0.35 L/D)**. The explication of this phenomenon is that the valve diameter is minor; consequently the area of the port is also narrow so the mass of the flow instead the valve lift will be less than a bigger port, however the drop of the air flow occurs at higher point. Why? The next explication is based on basics fluid theorems and theory's and will help to explain why this is happening:

- Inside the port there are **two types of flows**, turbulence and laminar flow. As it name says, turbulence flow is a irregular and chaotic flow, particles is moving disorganised and the direction are making small swirls, however the laminar flow is a perfectly tidy movement of the flow.
- In the interior of the port also the **Venturi's tube** can be applied: Is a tube with a gradual stretched in the tube section and a gradual widening to avoid the turbulences, the fluid speed in the stretched area is bigger than the wider area, also the pressure in the stretched is less than the wider section of the tube. The following image will show the explication.

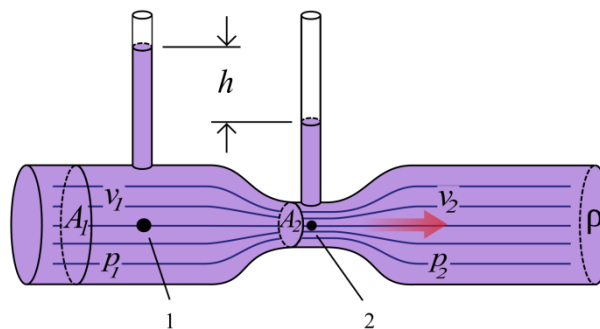


Figure 9: Ventuis tube

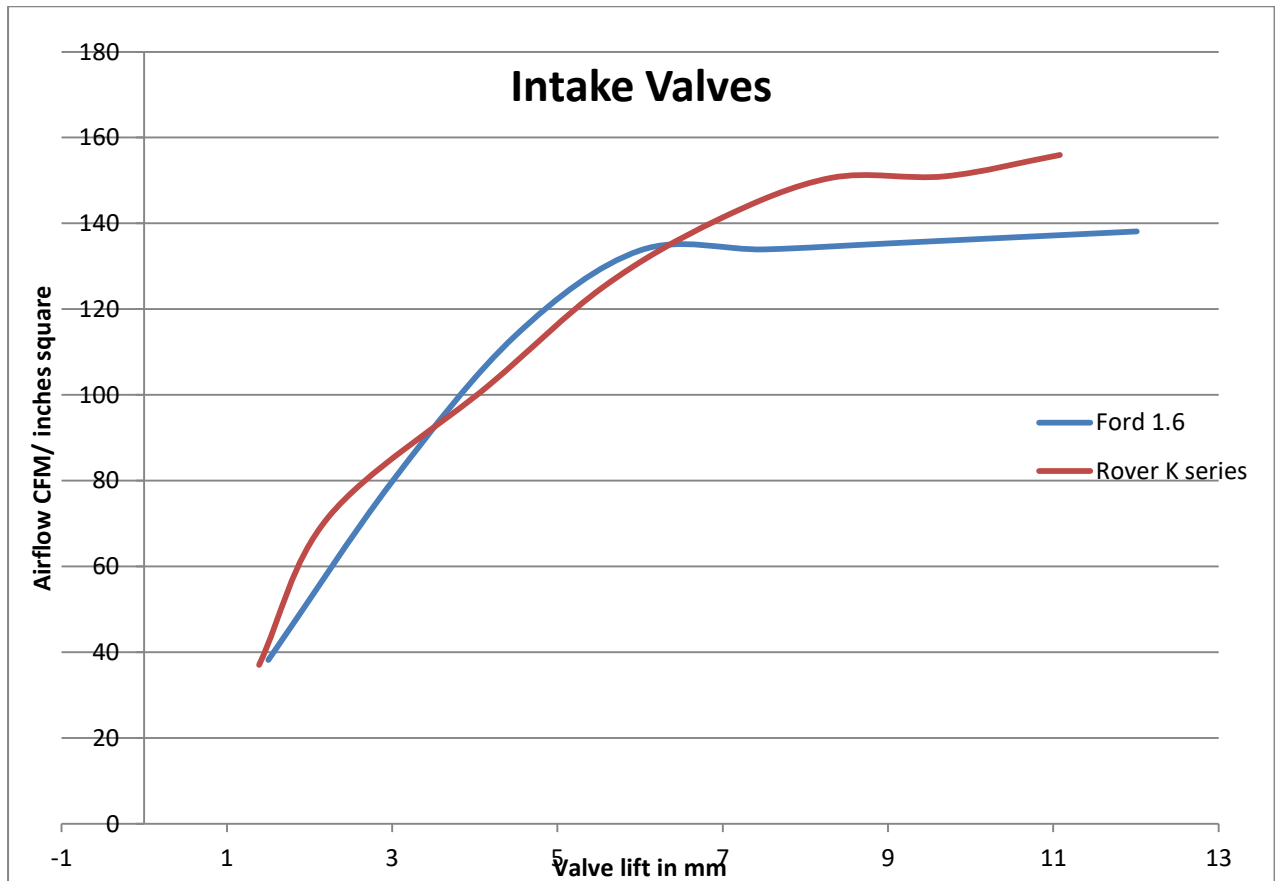
So, knowing this explication and the formula we can conclude why the drop in the Rover engine occur in a higher valve lift than in the Ford engine.

Analysis of Exhaust Graph

The graph shows the same pattern for the Ford and for the Rover engine, the average airflow is less in both cases due to one simple explication, exhaust valves must be smaller than the intake valves to dissipate the heat created in the chamber due the power stroke. Also the increases in volume are the reasons due to the valves have fewer diameters. Also knew as volumetric dilatation. The drop in the ford engine occurs at **0.3 L/D mm (7.23 mm) valve lift**. However in the Rover engine occurs at

0.35mm L/D (8.34 mm) valve lift. Why? The same explication as before, as fewer diameters, less flow, less area and more velocity and controlled more time. It can observed in both trending lines a small curve, positive in the Ford line and negative in the Rover line, is due to a mistake measured along the test. Each mistake is multiplied by the flow rate and in consequently is increasing the number calculated for the air flow in CFM.

5.2 CFM / inches square Vs Valve lift



The graph above however shows the quantity of the flow into the inlet port per area, in function of the valve lift. As shows as less valve diameter, less airflow per area. The perfect demonstration of the Bernoulli's Theorem: *The principle of Bernoulli says that the sum of potential and kinetic energies, in the various points of the system, is constant, if the flow is constant. When the diameter of a tube is modified, the speed also changes.*

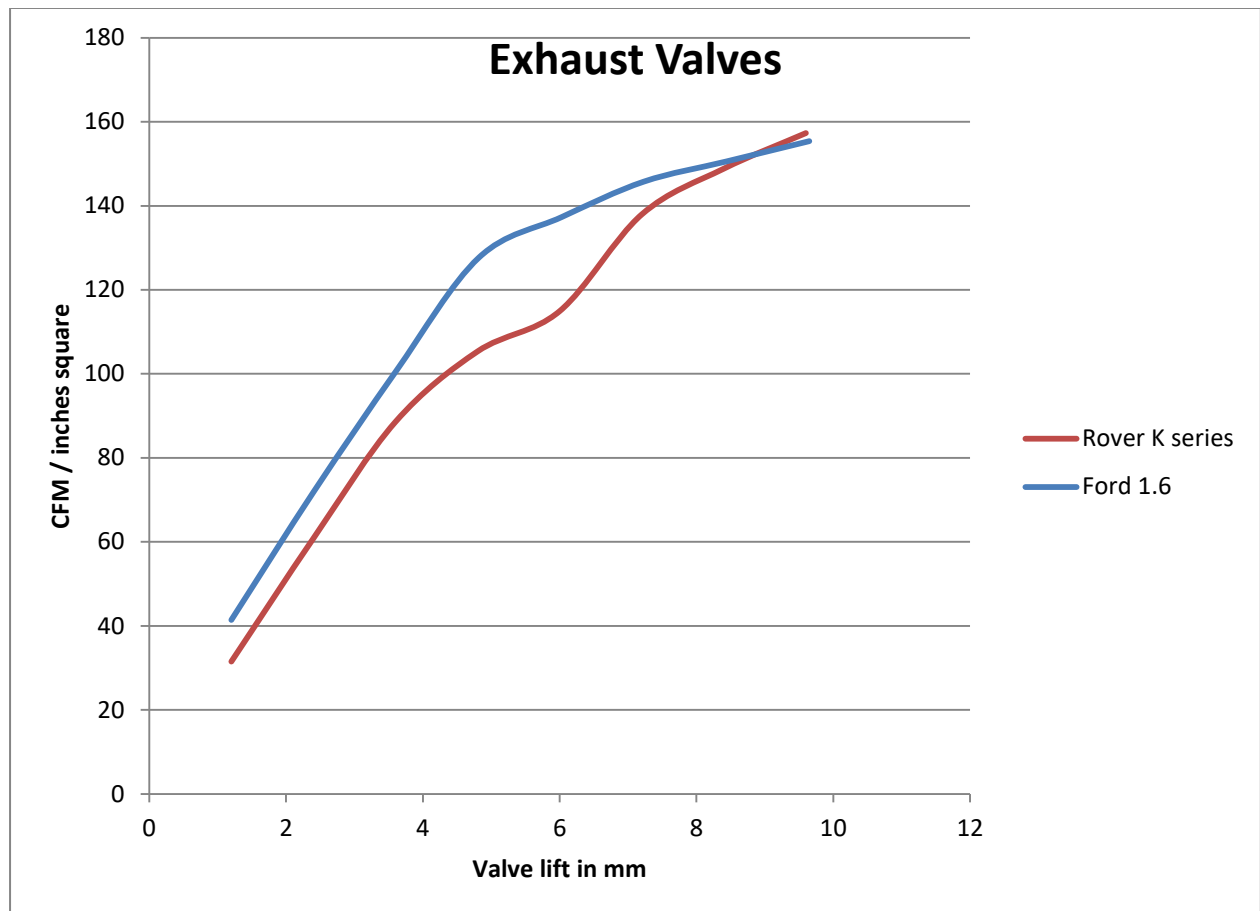
$$\frac{V^2 \rho}{2} + P + \rho g z = \text{constante}$$

Where V is fluid speed, P is pressure, g is 9.8, z is the height and ρ is the density of the fluid. So, if the energy is constant and the energy is kinetic energy and potential energy, if the kinetic energy increase, the velocity increases due to the formula of the Kinetic energy:

$$KE = 0.5mV^2, \text{ where } m \text{ is mass and } V \text{ velocity.}$$

Applying this formulas and the Venturi tube explained before, more energy, more velocity, and consequently more airflow in less surface.

Both graphs show a drop at the same point of valve lift as before due to the same explication of the movements of the air inside the chamber (swirl, tumble).



This graph is almost the same as the CFM Vs valve lift. The explication is due the surface of the exhaust vales is almost the same, and the CFM / inches square depends directly of the size of the valves. The effective area of both engines are 0.66 and 0.65 mm². The explication of this pattern is explained in the same graph above, the difference is just the CFM is divided by the area and us basically the same. Same mistakes and same airflow for almost same valve surface.

6. Conclusion

Since the type of cylinder heads to the forces applied when the air comes into the chamber has been studied along the assignment. A fully test was carried out to compare 2 cylinder heads include inlet and exhaust ports. It can see very easy the difference between the inlet and the exhaust valves, consequently the inlet and the exhaust port design. We can conclude the relevance of the design of the ports, the shape and the diameter of them. Also we can see how much could be improved the airflow seeing the tuning flow (% of potential flow) the difference between the data table and the potential flow is the amount of air flow capable for each port. Also knowing the fluid theorems we can see the importance of the gravity in a fluid, the area contained the fluid and the velocity of the air and how the flow and the pressure depends of the velocity, the area and the height of the system.

Improving the airflow of the system is one of the most important achieves in terms of power output. Porting is one of the common advances to improve the airflow of the cylinder head of an engine, is used for race and creates different shapes to improve the movement inside the cylinder ports

improving consequently the swirl and tumble movement of the mixture of air. Also is most important the shape inside the port instead to get bigger the ports, the Venturis tube define this theory.

Finally and to get good result the test was carried out 3 times to get better data of the flow bench. Every decimal number up or down makes a big mistake due to is multiplied by a ratio to calculate the final air flow of the system.

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